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Nanosecond Risetime Pulse Characterization of SiC p$^+$n Junction Diode Breakdown and Switching Properties

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Abstract: Single-shot nanosecond risetime pulse testing of SiC devices is demonstrated to reveal unique and highly crucial device performance information not obtainable by conventional DC and RF electrical testing. This paper describes some strikingly important device behaviors observed during pulse-testing experiments of 4H-SiC p$^+$n junction diodes. Specific observations include: 1) a remarkably fast and catastrophic diode failure mechanism in which an SiC diode fails at a fast-risetime pulse amplitude well below the DC-measured breakdown voltage, 2) positive temperature coefficient of breakdown voltage behavior in selected 4H-SiC diodes, and 3) average minority carrier lifetimes extracted from reverse recovery switching transients that are dominated by device perimeter surface recombination effects instead of the carrier lifetime inherent to the bulk SiC material itself. All three of these pulse-revealed behaviors provide important insights into fundamental physical issues that impact the performance and reliability of SiC-based electronics, especially high-power SiC devices.

1. Introduction

Both unipolar and bipolar SiC device electronics are being developed to meet the specific needs of various high-power and/or high-temperature applications. The vast majority of electrical measurements reported to date on prototype SiC devices have been quasi-DC current versus voltage curves recorded using conventional semiconductor parameter measurement instruments. While these measurements are an important first step in ascertaining device capabilities, the limited testing conditions do not necessarily reflect operating conditions that SiC devices will encounter in real world electronic systems. In order to function with the acceptable levels of reliability, it is essential that SiC devices, particularly in aerospace power conversion and motion control system circuits, be able to withstand overvoltage glitches that commonly occur in these systems without sustaining physical degradation or damage. Likewise, these devices will also have to operate efficiently with low losses at high switching speeds. By example of testing p$^+$n diode rectifiers, this paper demonstrates the utility of single-shot nanosecond risetime pulse testing in effectively analyzing the reverse breakdown reliability, reverse recovery switching speed, and minority carrier lifetime of SiC-based devices.

2. Experimental

Pulse testing was carried out using the charge line circuit depicted in Fig. 1. This circuit nominally stressed the device under test with rectangular shaped pulses of 200 ns width (nominal 1 ns risetime with non-inductive loading) on a manually triggered single-shot basis. The pulse voltage amplitude was controlled by adjusting the HVDC supply, which charged a 1/2-inch 150-ft semirigid transmission line. The input voltage pulse to the diode is formed by the discharge of the semirigid coax when the mercury vapor switch is momentarily triggered. The current probe monitors transient diode currents over the frequency range from 1 kHz to 500 MHz. The DC bias portion of the circuit (the 10 µF capacitor, DC supply, and 200 or 400 Ω resistor) supplies an initial forward bias to the diode for the reverse recovery switching transient measurements of Section 4, and is not present for the reverse breakdown testing described in Section 3. All diodes presented here are mesa-isolated 4H-

SiC epitaxial p$^+$n junction diodes, whose detailed device structure and fabrication procedures are discussed individually elsewhere [1-4].

3. Reverse Breakdown Testing and Power Device Reliability

This section briefly summarizes how pulse testing revealed vastly differing reverse breakdown reliability properties from two sets of diodes that had very similar DC I-V characteristics. The 4H-SiC diodes from NASA Lewis Lots #1841 [1,2] and #1905 [3] both exhibit nearly identical low leakage and near 140 V DC breakdown voltages when measured on a conventional curve-tracer. The sharply contrasting data of Figures 2 and 3 illustrates vastly different breakdown reliability properties revealed when the two lots underwent fast-risetime reverse-bias pulse-testing. The #1841 4H-SiC diode of Fig. 2 fails catastrophically less than 20 ns into the application of a single 94 V fast-risetime pulse, as evidenced by the large current drawn and the fact that the diode transitioned from a rectifying I-V when tested on the curve tracer prior to the pulse to a short-circuit immediately following the pulse. This extreme susceptibility to a single fast risetime glitch pulse of amplitude well below DC breakdown is clearly unacceptable for power applications requiring high reliability.

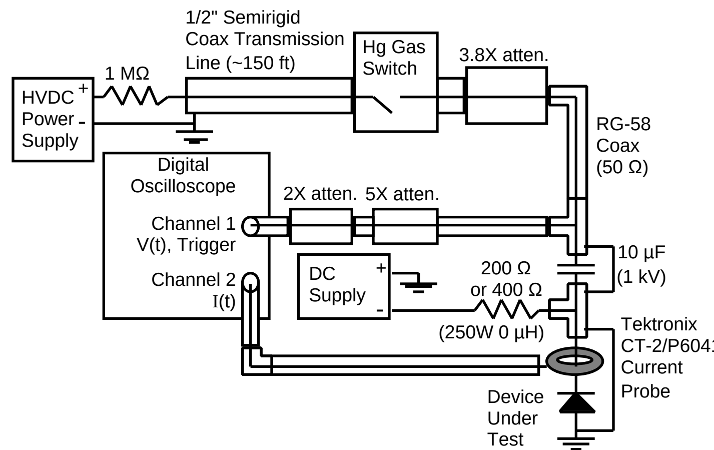

Fig. 1. Fast risetime pulse testing circuit.

In stark contrast to the unreliable device of Fig. 2, Fig. 3 shows the #1905 4H-SiC diode successfully withstanding (without physical junction damage or failure) a pulse amplitude of 322 V, more than twice the 140 V DC-measured breakdown voltage. The #1905 junction is highly immune to overvoltage glitches in large part because it exhibits the desirable property of positive temperature coefficient of breakdown voltage, witnessed in Fig. 3 by the breakdown voltage increase coupled

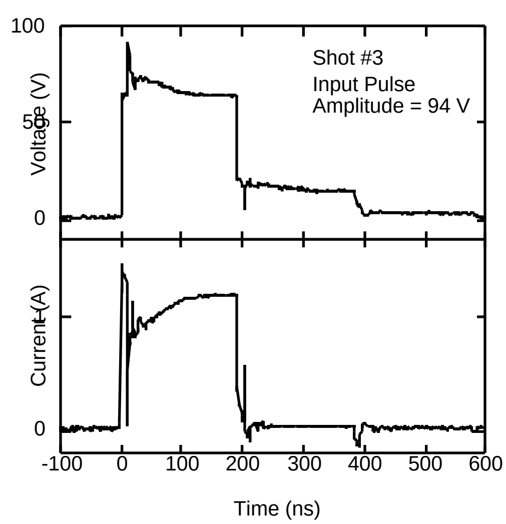

Fig. 2. Pulse-test transient current and voltage waveforms showing catastrophic failure (typical of 4H-SiC p$^+$n devices in Lot #1841) less than 20 ns into the application of a single 94 V fast-risetime reverse bias pulse [1,2].

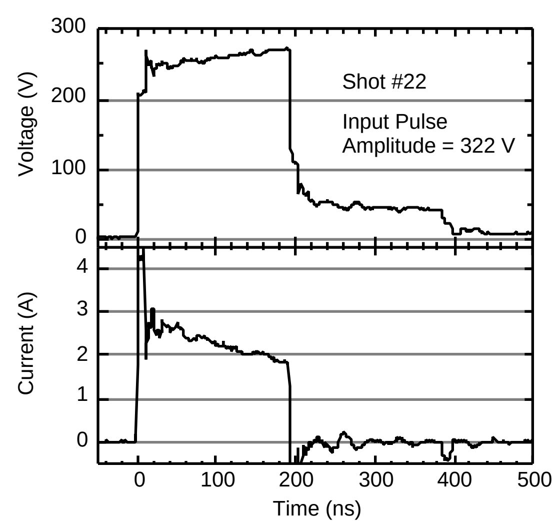

Fig. 3. Pulse-test transient current and voltage waveforms from small-area 4H-SiC p$^+$n diode (Lot #1905) showing positive temperature coefficient of breakdown voltage behavior. The diode withstands the pulse without damage [3].

with breakdown current decrease as the device self-heats over the 200 ns breakdown-bias pulse application. Because current flow at localized hotspots is decreased by positive temperature coefficient behavior, the formation of high intensity current filaments is prevented during first breakdown leading to a more reliable SiC rectifier [1-3,5].

The physical reasons for the startlingly different breakdown behaviors between Lots #1841 and #1904 are not fully understood at this time. Recent SIMS analysis has indicated a higher compensating aluminum impurity concentration in the n-layer of Lot #1841 as well as an undesired increase in atomic N at the metallurgical junction which may contribute to the observed breakdown instability. The presence of crystal defects, deep levels, and incomplete ionization of dopants may also play some role in the breakdown physics of SiC pn junctions [1,2].

4. Reverse Recovery Switching Analysis and Perimeter-Governed Carrier Lifetime

In bipolar devices the recombination lifetime of minority carriers injected across pn junctions plays a key role in determining device performance, since gain, maximum current rating, and maximum operating frequency are inherent functions of minority carrier lifetime [5-7]. Prototype SiC bipolar devices reported to date have exhibited minority carrier lifetimes well below 1 µs. While beneficial for high switching speed, these short lifetimes have effectively limited experimental SiC bipolar device current densities and gains.

We employed the fast-risetime pulse circuit of Fig. 1 to measure reverse recovery switching characteristics and effective minority carrier lifetimes of epitaxial 4H-SiC p^+n junction mesa diodes (N_D = 2 - 4 x 10^{16} cm^3) from Lot #1904 [4]. See Ref. [6] for fundamental reverse recovery physics. Fig. 4 shows two sample reverse recovery current transients recorded when a 4H-SiC diode was rapidly switched from an initial forward bias of 0.65 A to reverse bias by respective 30 V and 40 V fast-risetime pulses. Parasitic inductive effects and current probe low-frequency limitations are responsible for non-idealities in the recovery current waveforms. Nevertheless, a relatively constant current storage phase regime is readily discernible from a strongly decaying recovery phase regime in each current transient, thereby enabling reasonably accurate determination of minority charge storage time t_s [6]. As shown in Fig. 5, storage times obtained from the measured recovery current transients tracked the classical dependence upon the ratio of OFF-state peak switching current (I_R) to initial ON-state forward current (I_F) given by [6]:

$$t_s = \tau_p \left\{ \mathrm{erf}^{-1}\left[1 + \frac{1}{I_R / I_F}\right]\right\}^2 \qquad \text{Eq. 1}$$

By fitting Eq. 1 to experimental plots of t_s vs. I_R/I_F (Fig. 5), effective hole minority carrier lifetimes (τ_p) were ascertained for each device.

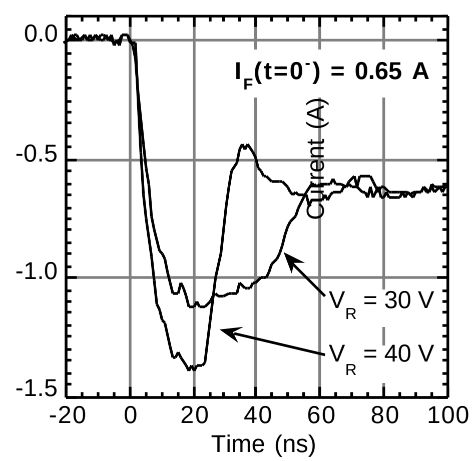

Fig. 4. Reverse recovery current transients recorded on 8.1 x 10^{-3} cm^2 4H-SiC diode. t_s ≈ 20 ns and 40 ns for I_R ≈ 1.4 A and 1.1 A, respectively. Because the current probe does not measure DC currents, the 0.65 A I_F is not reflected in the transients for t < 0.

The minority charge storage times (t_s) and minority carrier lifetimes (τ_p) both strongly decreased with decreasing device area, which indicates that the measured hole lifetime τ_p is not the bulk carrier lifetime inherent to the SiC epilayer. It is well documented in other semiconductors that when bipolar current densities, diffusion lengths, and/or carrier recombination lifetimes decrease with decreasing device size, the physical mechanism of perimeter surface recombination occurring around the junction perimeter is usually responsible [7]. The bulk and perimeter contributions to device average minority carrier lifetime can be separated by plotting $1/\tau_p$ as a function of device perimeter-to-area ratio (P/A) as shown in Fig. 6 [4]. This plot reveals that perimeter recombination is dominant in these devices, whose areas are all less than 1 mm^2. The bulk minority carrier lifetime extracted from the $1/\tau_p$ vs. P/A plot is approximately 0.7 µs, well above the 60 ns to 300 ns apparent lifetimes obtained when perimeter recombination effects are not properly taken into account.

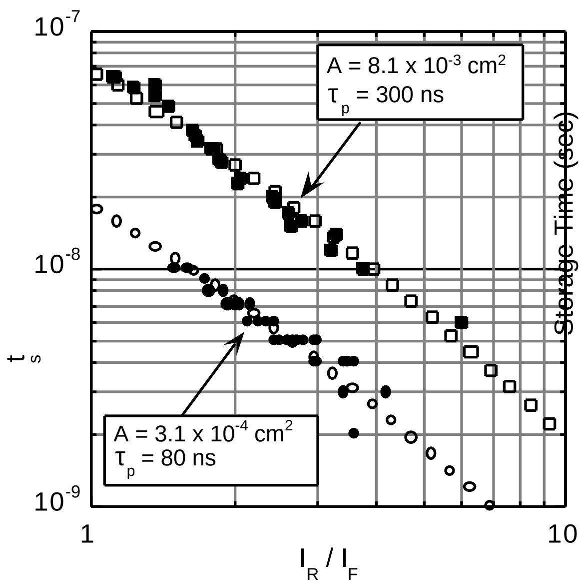

Fig. 5. Dependence of diode minority carrier charge storage time (t_s) on I_R/I_F ratio for two different 4H-SiC diodes from the same wafer. Open symbols are plots of Eq. 1 calculated using τ_p that fits experimental data (filled symbols) from each device.

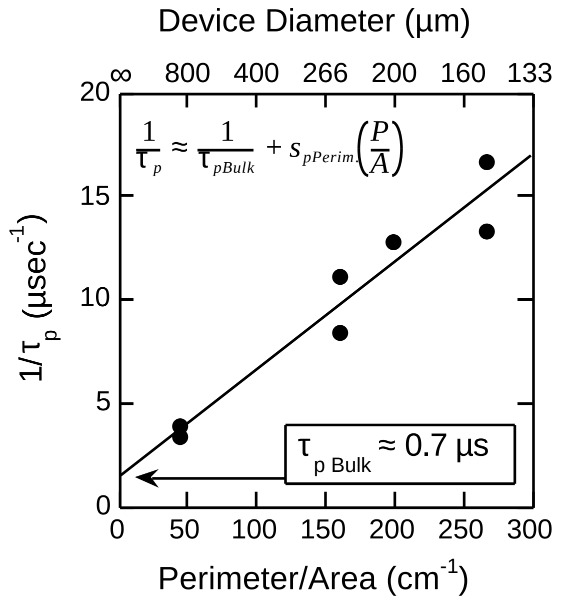

Fig. 6. Effective inverse minority carrier lifetime ($1/\tau_p$) plotted as a function of device perimeter-to-area ratio. The steep slope indicates that surface recombination around the etched diode perimeter dominates the effective minority carrier lifetime of the device, instead of recombination occurring in the bulk SiC epitaxial layer.

While almost all prototype SiC bipolar devices reported to date have been small-area (< 1 mm^2), there has been little investigation of SiC bipolar device performance as a function of perimeter-to-area ratio. This work raises the possibility that perimeter recombination effects may be partly responsible for poor effective minority carrier lifetimes and limited performance obtained in many previous SiC bipolar junction devices.

5. Summary

This paper has demonstrated the ability of fast-risetime pulse testing to reveal important SiC device behaviors not observable by conventional quasi-DC and RF electrical testing methods. Reverse-bias pulse testing yielded important device reliability information, while forward-to-reverse switching analysis demonstrated effective bipolar minority carrier lifetimes dominated by perimeter surface recombination instead of bulk SiC material quality. These observations strongly suggest that fast-risetime pulse-testing should play an important role in the development and qualification of SiC electronic components.

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